

Tribological effects of polymer surface modification through plastic deformation

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Abstract. The efficacy of using polymers in cylindrical applications depends closely on its surface friction and wear characteristics. In this regard, a surface modification technique through plastic deformation has been implemented. Roller burnishing is commonly used to improve the surface quality of non-ferrous surfaces, but no work showed concern about roller burnishing as a polymer surface treatment process. The objective of the present work is to investigate the influence of burnishing force and burnishing speed on the friction and wear performance of acetal homopolymer and polyurethane under dry and lubricated sliding conditions. The results reveal that the coefficient of friction and wear rate decreased to a minimum value and then increased as higher burnishing force and speed were applied. It was shown that roller burnishing had favourable prospective to be utilized as a valuable polymer surface treatment technique.

Keywords. Roller burnishing; acetal homopolymer; polyurethane; coefficient of friction; wear rate.

1. Introduction

Roller burnishing process is a chipless post machining operation traditionally used to improve the surface qualities of non-ferrous components by removing scratches, tool marks, pits and porosity (Hassan and Al-Bsharat, 1996, 1997). In this process, surface of the workpiece is compressed by the application of a highly polished and hardened roller subjected to external force. When the applied pressure exceeds the yield strength of the material, the asperities displace permanently into the valleys resulting in a smooth and uniform surface. Roller burnishing distinguishes itself from other post machining operations as it is capable of enhancing the mechanical properties of the surfaces as well. Previous works reported that roller burnishing imparts an increase in the hardness, tensile strength and yield strength, as well as generating compressive residual stresses in the surface region which could mitigate fatigue cracks (Hassan and Al-Bsharat 1996, 1997; Zhuang and Halford 2001; El-Axir and El-Khabeery 2003; Prev y and Cammett 2004). In addition, roller burnishing also improves the surface roundness and dimension stability, which play a vital role in the fit and tolerance of assembled parts (El-Axir and El-Khabeery 2003).

With the current impetus of polymers being extensively used to substitute metallic and non-ferrous

components due to their excellent properties (Alauddin *et al* 1995), tribological characteristic is an important aspect when polymers are used in components such as bearings, gears and cams. An alleviation in energy dissipation (friction) and surface damage (wear) could translate to an improvement in accuracy, reliability and service life of the mechanical systems. Current polymer surface treatment technique includes grinding, particle beam irradiation and plasma treatments (Alauddin *et al* 1995; Cazzato *et al* 1996; Dong and Bell 1999; Hu and Zhang 2004), with no work showing any concern about roller burnishing of polymers. However, there is a strong possibility that roller burnishing process can be used to improve the friction and wear characteristics of polymeric surfaces since they can be machined and treated mechanically. Previous researches (Hassan and Al-Bsharat 1996, 1997; Zhuang and Halford, 2001; El-Axir and El-Khabeery 2003) on non-ferrous materials indicated that different burnishing parameters like force, speed, feed rate, number of tool passes, roller dimensions, etc may yield different results, therefore, selection of the burnishing parameters for polymers is crucial. El-Tayeb *et al* (2008) investigated the effect of roller burnishing process and reported that the surface roughness of POM-H and PU was decreased by 32–37% and 28–32%, respectively. The main objective of the present paper was to focus on the effect of burnishing force and burnishing speed on the friction and wear characteristics of polymers.

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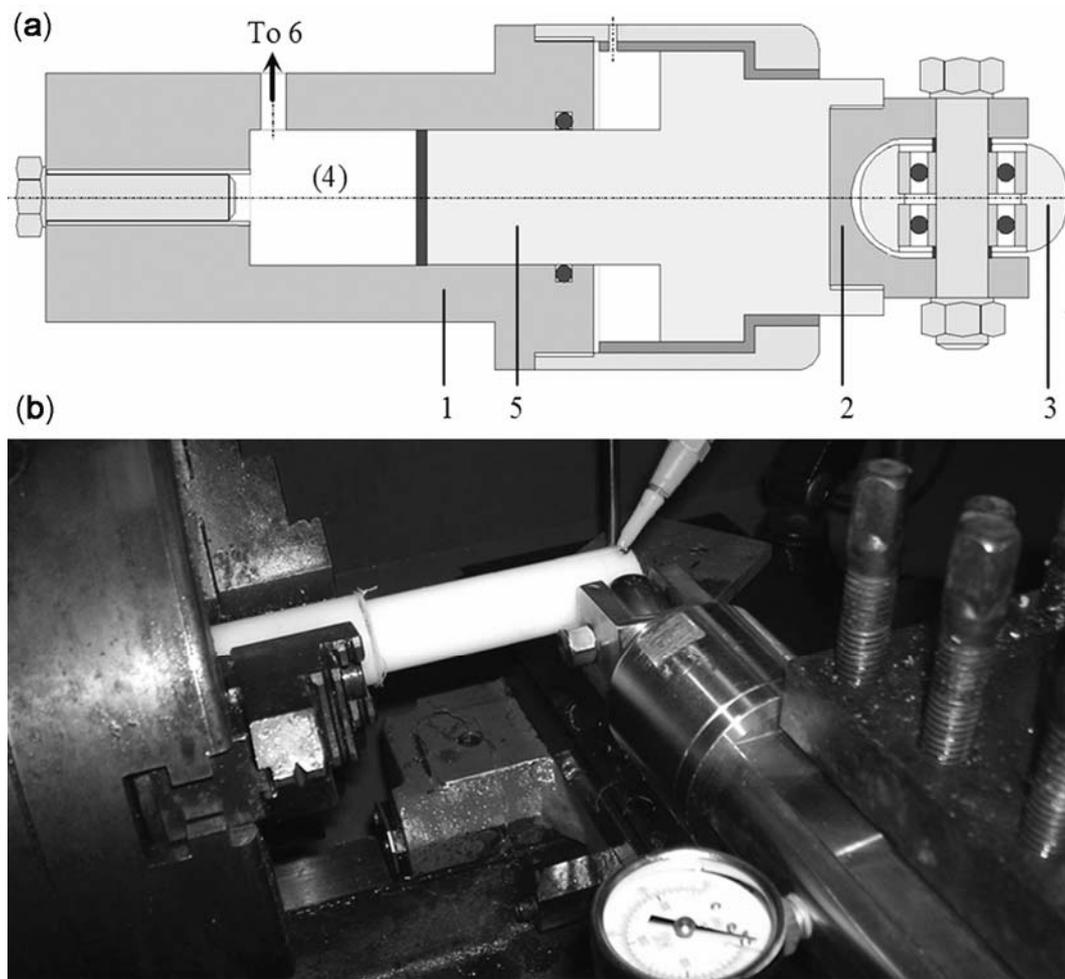


Figure 1. (a) Schematic view of roller burnishing tool (1. shank; 2. roller adapter; 3. burnishing roller; 4. hydraulic chamber (pressure); 5. guide rod; 6. pressure gauge) and (b) photograph showing roller burnishing process.

Table 1. Details of selected materials.

| Properties | POM-H | PU |
|-----------------------|------------------------|------------------------|
| Scientific name | Poly(oxymethylene) | Polyurethane |
| Trade name | Delrin® | Tufset® |
| Tensile strength | 70 MPa | 25 MPa |
| Flexural strength | 90 MPa | 65 MPa |
| Specific gravity | 1.42 g/cm ³ | 1.20 g/cm ³ |
| Melting point | 175°C | NA |
| Modulus of elasticity | 3.3 GPa | NA |
| Water absorption | 0.9% | 0.13% |
| Service temperature | -50°C-100°C | -100 to 100°C |

2. Experimental

2.1 Materials specification and specimens preparation

The polymers used were commercially available acetal homopolymer, POM-H (thermoplastic) and polyurethane, PU (thermoset) supplied by TNG Ltd., Malaysia. The

properties of the materials are specified in table 1. The selection of polymers was based on their importance in industrial applications. For instance, POM-H has excellent mechanical and machining properties and is widely used in bearings, precision gears, rollers and transport conveyors, while the low friction and high abrasion resistance characteristics of PU render it favourable for bearings,

guides and bushing. The polymers were received in cylindrical rods and were initially turned into circular discs of 25 mm diameter. Roller burnishing operations were performed using specially designed burnishing tool attached on a LA430 lathe machine (figure 1). The tool consisted of a highly polished and hardened carbon chromium roller, which was fed parallel to the axis of the rotating workpiece and it rotated due to the frictional engagement between the contacting bodies. Burnishing force was applied onto the surface using hydraulic pressure and the corresponding axial sliding motion of the guide rod was detected by a pressure gauge. The variables chosen in this study were the burnishing force, F (60 to 360 N) and the spindle or burnishing speed, n (110–490 rpm). Single pass burnishing with 0.087 mm/rev feed were used throughout the burnishing process.

2.2 Friction and wear tests

After burnishing, the burnished specimens were removed from the lathe machine and attached to a laboratory-built tribo-test machine (figure 2) for friction and wear tests. The specimen was clamped into a holder in such a way that the burnished direction was either in parallel or crossed orientation of sliding (PB-O or CB-O) as shown in figure 3. The specimen was loaded normally with 20 N weights through a loading lever. During the test, friction forces at the sliding interface were detected using a load cell arrangement mounted on the loading lever. The loading lever was balanced by a balancing weight to ensure no initial normal load was present. A 60 mm diameter stainless steel counterface cup was used throughout the test. It was regularly refreshed using an abrasive paper

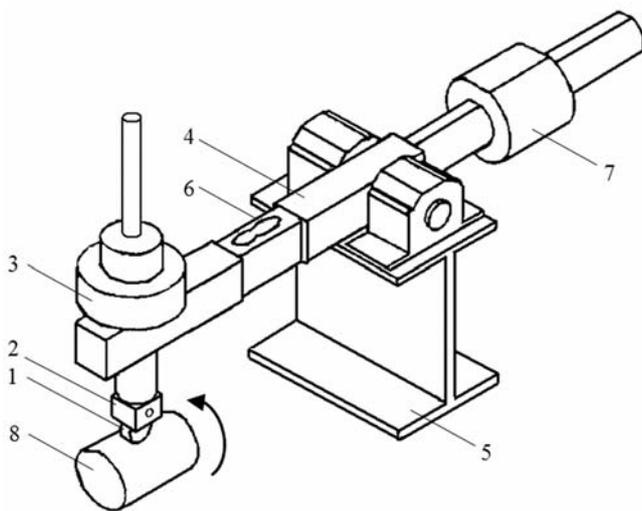


Figure 2. Schematic diagram showing the tribo-test machine (1. specimen; 2. specimen holder; 3. dead weight; 4. loading lever; 5. frame; 6. load cell; 7. balancing weight; 8. counterface cup).

(silicon carbide coated 600 grade) to an average roughness of 0.26 μm before each test. A light viscosity lubricant (SAE 20W/40) was used when tested under lubricated contact condition. Weight loss measurements were taken using an analytical balance of 0.1 mg resolution (Shimadzu AW220) after a running-in period of 180 s at a constant rotational speed of 200 rpm (which is equivalent to a sliding velocity of 0.6283 ms^{-1} and a sliding distance of 0.113 km). The specific wear rates (mm^3/Nm) were deduced from the mass loss, and the inverse of specific wear rate is generally referred to as wear resistance. Figure 4 presents the coefficient of friction and specific wear rate for turned surfaces (unburnished) under various conditions. Microscopic studies of the surfaces were carried out using a scanning electron microscope (JEOL JSM840A). Each specimen had to be gold coated before SEM investigation to enhance its conductivity.

3. Results and discussion

3.1 Friction behaviour

Figure 5 shows the effect of burnishing force on coefficient of friction under parallel and crossed burnished orientations (PB-O and CB-O). In the case of dry sliding condition for PB-O (figure 5a), the coefficient of friction decreased, i.e. improved with increasing burnishing force reaching up to 26.8% and 17.7% reduction at 250 N for POM-H and PU, respectively and then increased slightly. The curves revealed that low burnishing force corresponded to a less reduction in the coefficient of friction. This may be ascribed to little or incomplete deformation action of the asperities caused by insufficient compressive action at low burnishing force leading to some asperities being partly deformed and appeared serrated. As a result, higher degree of mechanical interlocking of asperities occurs during sliding. It can also be clearly seen that interposing lubricant at the sliding interface reduces the coefficient of friction for both polymers. This decrease is associated with the separation at interface by boundary lubricant film leading to lower temperature and smoother sliding action. A similar trend was observed for both polymers when sliding test was conducted under CB-O (figure 5b). While a decrease in coefficient of friction was achieved in all burnishing force conditions, the lowest value was again achieved at burnishing force of 250 N corresponding to 21.7 and 19.8% improvement for POM-H and PU, respectively.

Figure 6 presents the influence of burnishing speed on coefficient of friction under parallel and crossed burnished orientations. The results for PB-O under dry sliding condition (figure 6a) revealed that less reduction in coefficient of friction was attained at lower burnishing speed (110 rpm) for both polymers, i.e. a mere 3.7%

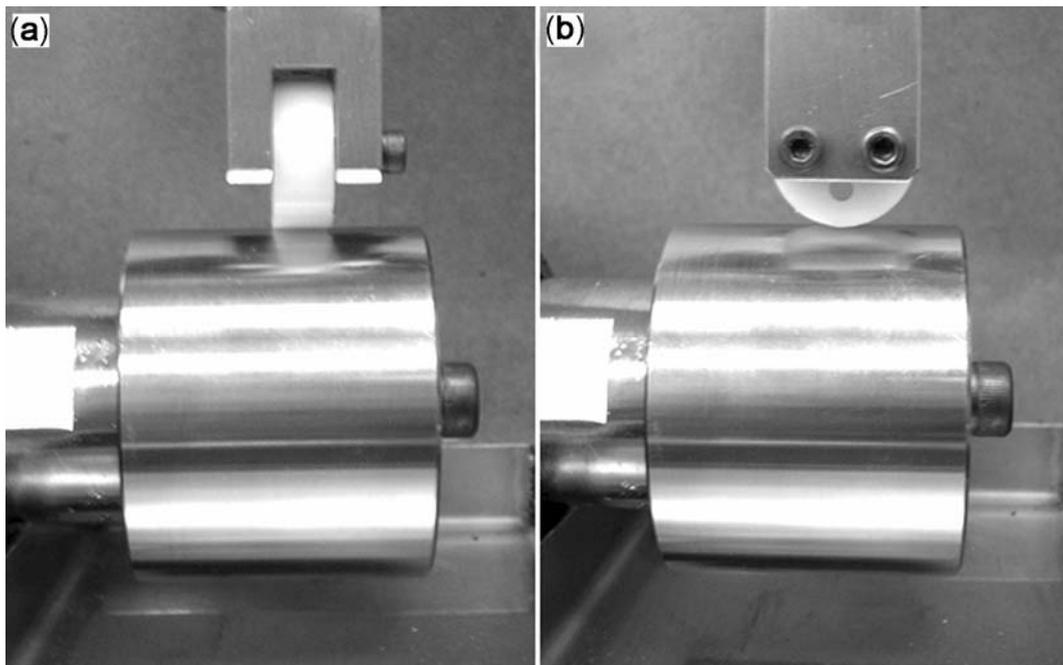


Figure 3. Tribo-test operations: (a) CB-O, cross burnished orientation and (b) PB-O, parallel burnished orientation.

and 1.8% decrease for POM-H and PU, respectively. This may be due to the ploughing and micro-cutting action of the rough asperities present at the polymer surfaces, which in turn elevated the friction. However, as the burnishing speed increased, the coefficient of friction decreased up to 26.8% (POM-H) and 17.7% (PU) at a burnishing speed of 330 rpm, beyond which it began to increase, indicating that greater deforming action and regular plastic flow due to burnishing took place. Burnishing at higher speed (490 rpm) still decreased the coefficient of friction, albeit at a lesser degree. This phenomena can be explained by the combined effects of two factors. In the first aspect, it has been reported that burnishing requires sufficient lubrication at the interface in order to improve the surface quality (Luo *et al* 2001), because sliding between two interface results in heat generation at asperities and hence an increase in temperature at the frictional surfaces. In this regard, it may be suggested that the reduced lubrication effect at the burnishing zone at high speed caused a rise in temperature, and as it continues to reach the softening limit of the polymeric materials, the adhesive component began to feature more prominently leading to higher coefficient of friction. In the second aspect, it is well known that the intensity of tool chattering increased at higher speed due to vibration (El-Axir and Ibrahim 2005). This local chattering not only restrained the deforming action of the burnishing roller but also may induce delamination and fracture of the surfaces. Similar explanation can be made for CB-O (figure 6b) since it exhibits similar trend. The coefficient of friction in the case of lubricated condition for both

orientations remained almost constant within the range studied, however, it can be seen that at all burnishing speed, a reduction in coefficient of friction was achieved.

3.2 Wear behaviour

Figure 7 shows the effect of burnishing force on specific wear rate under parallel and crossed burnished orientations. For PB-O under dry sliding condition (figure 7a), wear decreased as higher burnishing force was applied, gaining as much as 25 and 27.8% improvement for POM-H and PU, respectively at 250 N. This may be explained by the decreasing trend exhibited by the coefficient of friction results at higher burnishing force values, where smoother surface with less asperities corresponds to less removal of material during sliding test. In addition, an increase in wear resistance also indicates that the work hardening effect due to higher burnishing force is more pronounced. Moreover, it may be suggested that the resulting surface texture due to roller burnishing increases the compressive residual stress at the surface layers, thus hindering the growth of cracks and wear delamination. On the other hand, low burnishing force, 60 N, tends to result in 9% degradation of the wear resistance of PU, probably because the insufficient pressure failed to reach the limit of thermosetting polymers like PU, giving rise to incomplete deformation action. Since the wear process in amorphous and brittle like materials such as PU is closely linked to fracture of asperities that takes place during friction process, the high wear rate of PU may be due to the high coefficient of friction values when high

burnishing force was applied (figure 5a). Accordingly, these fractured particles may further result in reshaping of the particle edges leading to higher wear rate as well which is evident from the SEM micrographs of the worn surfaces shown in figure 8. The examination of worn surface burnished at 60 N revealed that a portion of rolled loose debris that accumulated on to the PU surface (figure 8a) acts as an abrasive third body to further abrade the surfaces causing groove marks, as compared to the surface burnished at 250 N, with the latter exhibiting a smoother surface consisting of superficial grooving marks as produced during sliding (figure 8b). However, when a layer of fluid or lubricant is introduced between the sliding surfaces, adhesion junction can hardly be formed due to attenuation of the van der Waals forces. As a result, adhesive wear would be significantly suppressed. Hence, for lubricated contact conditions, there is an almost negligible decreasing trend in wear rate for both polymers with increasing burnishing force although improvements

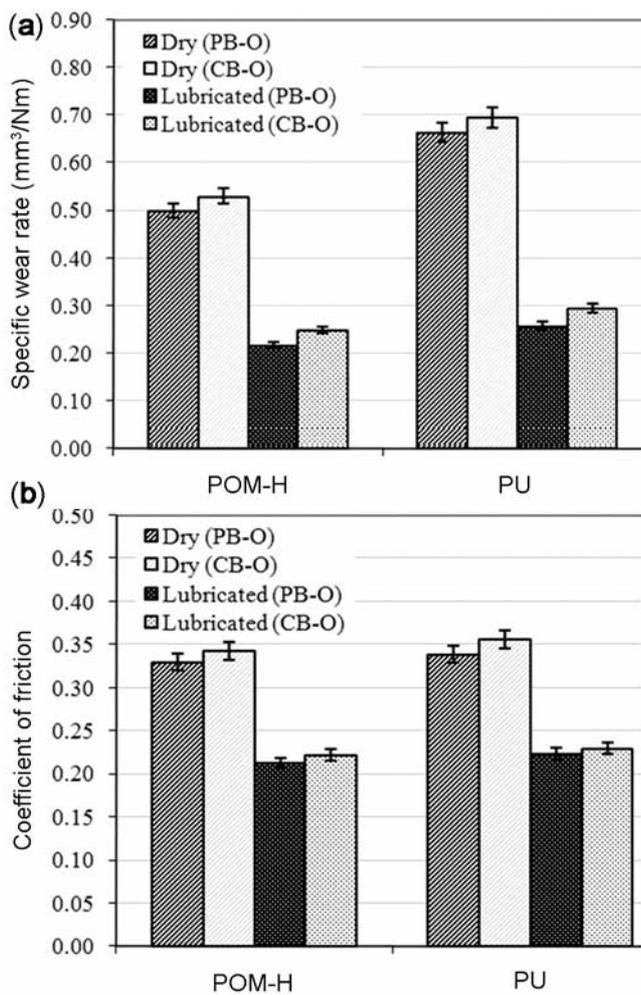


Figure 4. Bar charts showing results of friction and wear tests for turned surfaces: (a) coefficient of friction and (b) specific wear rate.

in wear resistance were achieved within the force ranges studied. This indicates that lubrication seems to stabilize the wear rate of burnished surfaces regardless of the

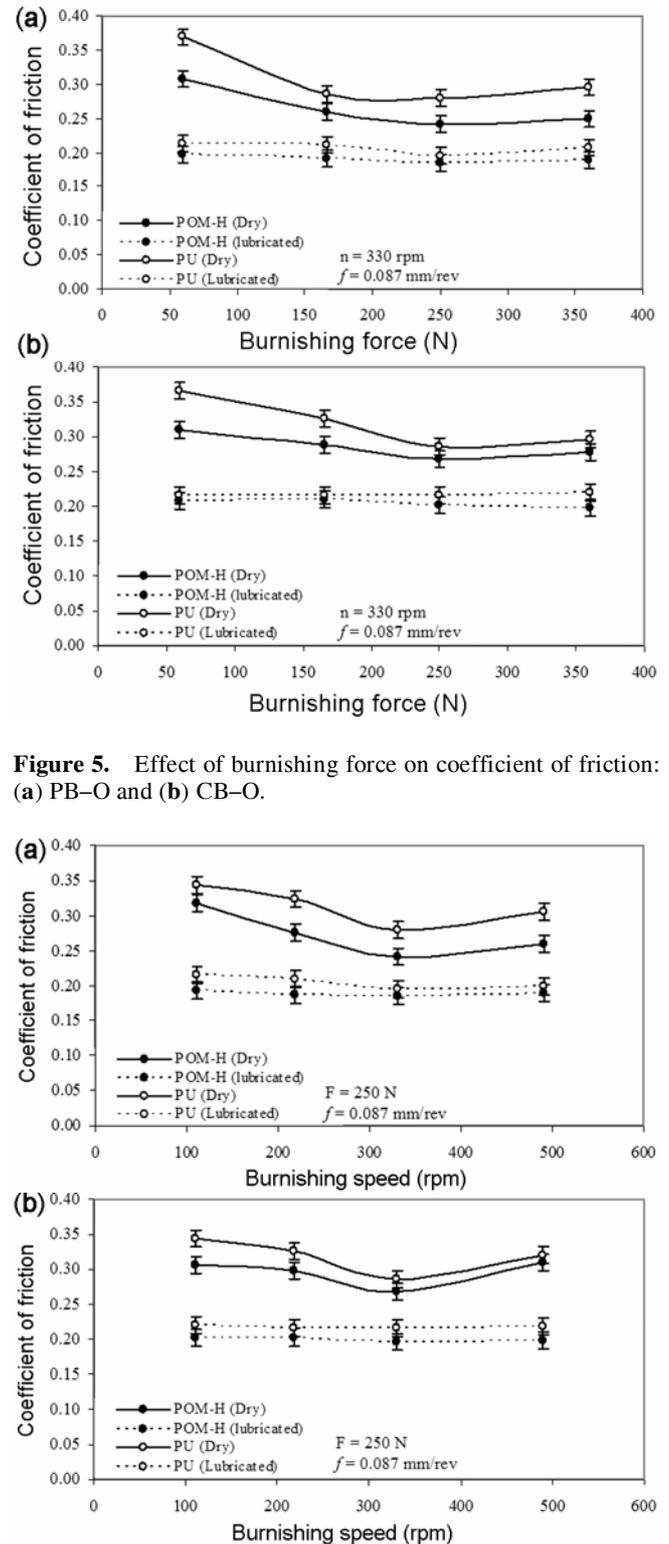


Figure 5. Effect of burnishing force on coefficient of friction: (a) PB-O and (b) CB-O.

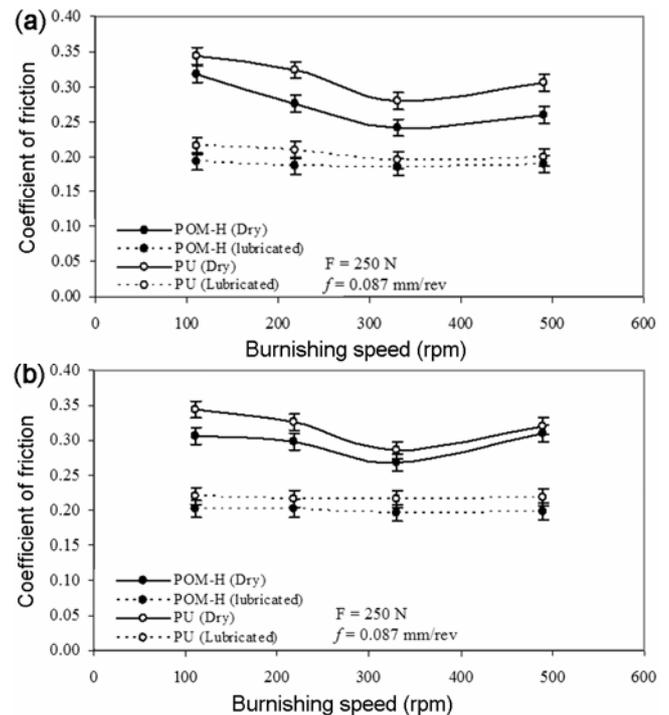


Figure 6. Effect of burnishing speed on coefficient of friction: (a) PB-O and (b) CB-O.

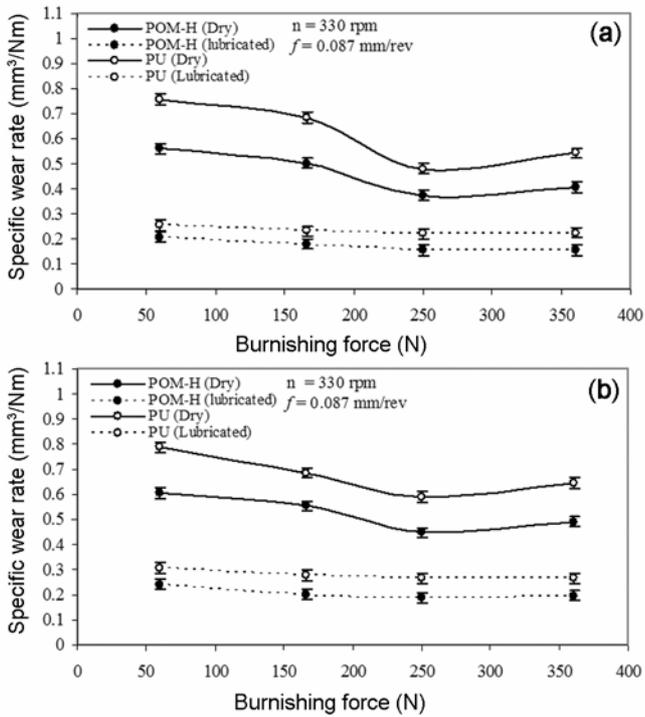


Figure 7. Effect of burnishing force on wear rate: (a) PB-O and (b) CB-O.

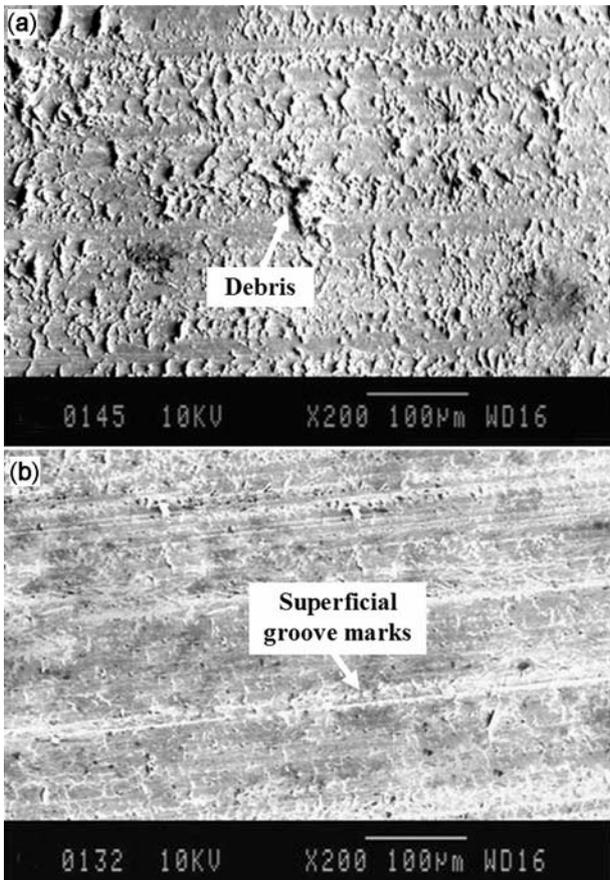


Figure 8. SEM photographs showing feature of worn PU surface under dry sliding PB-O condition: surface burnished (a) at 60 N and (b) 250 N.

applied burnishing force. Similar findings were observed in the case of CB-O (figure 7b).

Figure 9 presents the effect of burnishing speed on specific wear rate under parallel and crossed burnished orientations. In the case of dry sliding condition for both PB-O and CB-O conditions, increasing the burnishing speed up to about 330 rpm tends to enhance the wear resistance of both polymers with POM-H showing lesser wear or surface damage than PU. In some non-ferrous components burnishing (El-Axir and Ibrahim 2005), similar enhancement was explained as greater deformation and regular plastic flow occurs, leading to better work hardening effect. This explanation could be extended to burnishing of polymers given that deformation and plastic flow featured more prominently in polymers. Nevertheless, it has been established in prior discussion that greater frictional heat is generated at high burnishing speed because lubricant loses its effect due to limited time to interpose between the burnishing roller and workpiece surface. This frictional heating promoted a temperature rise in the burnishing zone and subsequently softening of the polymer surfaces. As a result, the wear regime can be severe, as featured in the SEM photograph in figure 10 of the worn surface subjected to high burnishing speed. In the case of dry PB-O sliding condition (figure 10a), POM-H material showed a wrinkle with wavy morphology surface and a surface degradation caused by melting which happens due to frictional heat

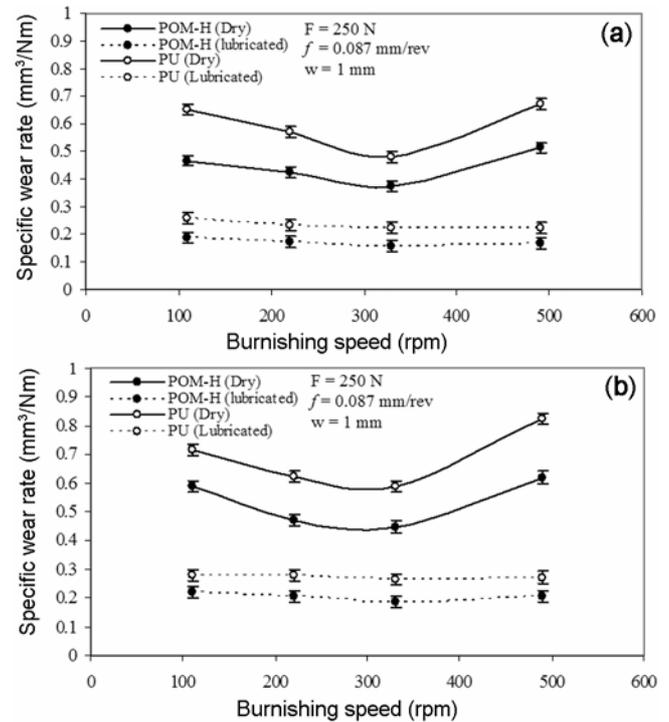


Figure 9. Effect of burnishing speed on wear rate: (a) PB-O and (b) CB-O.

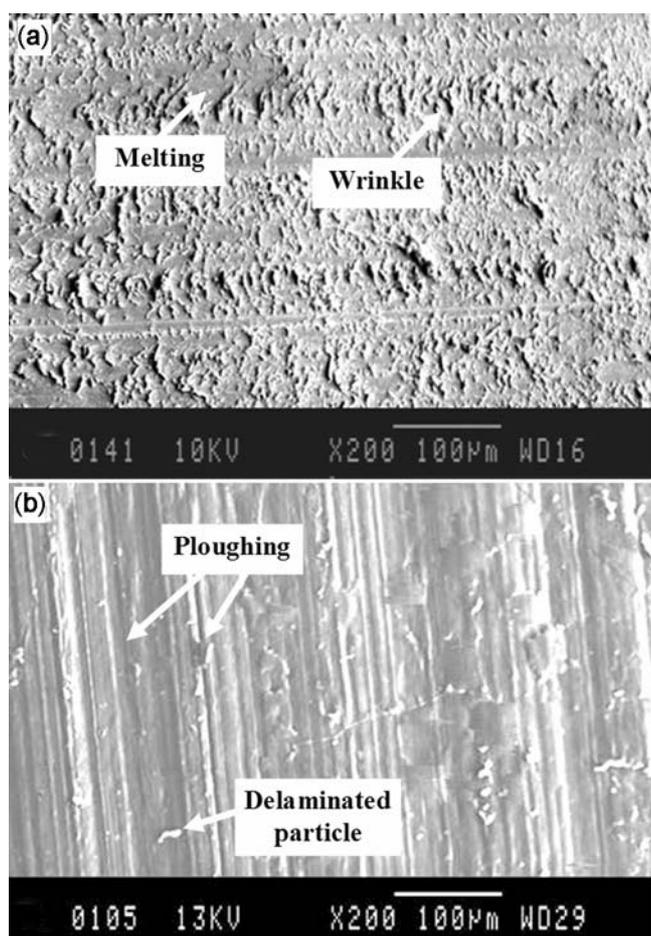


Figure 10. SEM photographs showing feature of worn POM-H surface burnished at 490 rpm under dry sliding condition: (a) PB-O and (b) CB-O.

usually associated at higher speed level. In the case of dry CB-O sliding condition, burnishing at high speed appears to offer little protection to the surface from damage. The POM-H worn surface suffered severe shear deformation with wider and deeper grooves caused by the aggressive action of metal asperities of the counterface as observed by surface characterization with SEM (figure 10b). In addition, the surface seems to be covered with thin flakes of delaminated particles which are probably due to local tool chattering effect at high burnishing speed. As a result, the wear regime due to micro-cutting can be radical, as can be affirmed by the results at high burnishing speed. However, such relationship between wear rate and burnishing speed was not displayed for both polymers when the

burnished surfaces were tested under lubricated condition, in which the variation of improvement in wear resistance was in the steady state region within the speed range used in this study. Generally, it may be suggested that the low values for the wear rate of POM-H as compared to PU was due to the existence of the transfer film on the POM-H surface.

4. Conclusions

The results indicate that roller burnishing is capable of enhancing the tribological properties of both polymers considered in this work. The coefficients of friction of the burnished surfaces were reduced up to 26.8 and 17.7% for POM-H and PU, respectively. At the same time, the wear rate decreased as much as 25 and 27.8% POM-H and PU, respectively. However, very high burnishing force and burnishing speed tend to result in degradation of surface quality.

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